Design and Prototype of a Partial Window Replacement to Improve the Energy Efficiency of 90-year-old MIT Buildings

by

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Submitted to the Department of Mechanical Engineering in
Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science
at the
Massachusetts Institute of Technology

June 2007

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Abstract

The existing windows of the 90-year-old buildings on the main MIT campus are not energy efficient and compromise comfort levels. The single panes of glass allow too much heat transfer and solar heat gain. In addition, the steel framework has warped due to oxidation and decay of the glazing compound, resulting in air and water infiltration.

This thesis explored a feasible solution of a partial window replacement that would not compromise the historical significance of the existing windows. The design and prototype demonstrated the replacement's functionality and preservation of aesthetic quality. The analysis showed an expected decrease in energy consumption of more than 70% and cost savings of nearly $2 million a year. The analysis also showed that comfort levels are higher throughout the year.

Thesis Supervisor: Leon R. Glicksman
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1 Introduction

The windows in the buildings on the main MIT campus—Buildings 1 through 11—have not been replaced since they were designed by architect William Welles Bosworth and built between 1916 and 1925.[1] There have been many window technology improvements such as the use of insulated glass units (IGUs), which are sealed double panes of glass filled with an inert gas, and low-emissivity coatings to control heat loss, solar gain, sunlight, and visible light transmissivity. The proposed window replacement can take advantage of these technologies.

The 90-year-old technology of the existing windows creates many problems today. The large, two-story windows comprise more than 50% of the total façade area. In the summer, the single glazed (single paned) windows with no coatings allow too much solar heat gain into the interior. As a result, occupants prefer to close the blinds and turn on the lights. In the winter, the rooms require more energy to heat due to heat loss from the highly conductive single glazing panels and steel framework. In addition, the sliding seal and the warped steel framework, a result of the decaying glazing compound and oxidation, causes significant air leakage. Cold air infiltration in the winter requires more heating energy, and cold air loss in the summer requires more cooling energy.

In order to improve the energy efficiency and comfort level of these buildings, I designed and built a prototype of a partial window replacement to retrofit a window in Building 1. The replacement reduces air leakage and solar heat gain while preserving the architect's initial designs.

The creation of such a prototype demonstrates a cost-effective way of improving the energy efficiency of more than just MIT buildings. Many old buildings outside of the MIT campus face similar problems in energy cost and can benefit from the adaptability of the design of this window retrofit.

2 Background

The Department of Facilities has considered various types of solutions, such as full window replacements, complete window restoration, and storm window inserts.[2] However, none of these concepts proved feasible mainly due to cost and the expected short lifespan. Building on the context of these discarded ideas, I propose a new concept that will address all problems.

2.1 Full Replacement

The Department of Facilities has quoted 80 million dollars as an approximation of the cost to replace all windows in the main buildings.[2] (See Appendix A for a map of the main group.) Aside from the required costs associated with removal and installation labor and materials, the total cost can be broken down into three portions. First of all, customization of the aluminum framework necessary to preserve the profile and aesthetics of the previous windows in such a historical building is expensive. Instead of separate panes of glass, using a big pane of glass (or IGU) with a pop-in framework of muntins is not a favorable option as it degrades the aesthetics and contradicts the architect's initial design.

The cost also includes accommodation of the spandrel panel, which is an opaque glazing used to hide the construction between floors. Finally, the most significant expense comes from the restoration of the masonry and limestone opening prior to a window replacement. Due to this high cost and a warranty of only ten years for IGUs, full replacement windows have been deemed infeasible.[2] An IGU fails when the desiccant around the perimeter of the window becomes fully saturated, and moisture begins to appear on the internal glass surfaces.[3] It can also fail due to improper choice of materials, UV degradation, and manufacturing defects.[3]

2.2 Other Designs

Applying caulking and putty to the framework would provide nothing more than a temporary solution to the air leakage. Also, it would not address the comfort level problem of solar heat gain due to the single glazing.

Window restoration would involve removing the glass panes, cleaning up the frame, applying a new sealing coat, and refitting the panes with new putty. Again, this would only temporarily improve the air infiltration. While restored windows offer low maintenance over the long term because there is no risk of glass failure, the system would continue to have poor energy efficiency.[4] The solar heat gain problem also remains unsolved.

A window insert on the exterior of the existing window would detract from the appearance of the building. However, a window insert on the interior, utilizing the ample ledge space, has already been implemented in the Engineering Conference Room in Building 1. The insert's framework is less extensive than the existing window's and does not affect the profile when viewed from the outside (see Figs. 1 and 2).

The use of aluminum frames with thermal breaks and IGUs significantly improves comfort level by reducing air infiltration and solar heat gain.[5] It is operable, but inconveniently so. The occupant must now open two sets of windows to gain ventilation. Some rooms have windows that are even more difficult to open due to the distance created by the ledge and the adjacent heater. Most of the existing double hung windows have a dual mechanism: when the bottom sash is pushed up to open, the top sash is pulled down by the same amount, effectively allowing for vertical ventilation. The window insert shown eliminates that helpful function.

Figure 1
Window insert (opened), interior view.

Figure 2
Window insert (closed), exterior view.

2.3 Conclusion

From this preliminary analysis, I determined that double glazed units are necessary for a window and overall energy efficiency improvement, despite the ten-year warranty (the IGU could potentially last for much longer). Double glazed units filled with an inert gas are much better for reduced heat transfer and reduced solar heat gain. Therefore, my concept focuses on removing the other two sources of cost (spandrel panel replacement and window opening restoration), maintaining the vertical ventilation function, and improving the operation of the window.

3 Methods

My design is a set of double glazed, hinged windows to replace a set of two sliding sashes. Hinged windows provide compression seals, and the Whole Building Design Guide concludes that "compression seal windows generally provide better long-term air infiltration and water penetration resistance than sliding seal windows because they reduce friction and wear on the weatherstripping."[6]

The replacement would cost less than the number suggested previously; since the existing external frame remains intact, the masonry and limestone need not be restored, and the spandrel panel may also be left as is. The four sashes in a two-story window comprise nearly half of the total window area, so the double glazing would reduce solar gain and improve comfort levels.

The hinge or hinges would be placed at the middle (see Variation (A) in Fig. 3) or near each end (see Variations (B) and (C) in Figs. 4 and 5), respectively, so that the vertical ventilation function is maintained, and the window would also be easier to operate (pulling in rather than pushing up). The lower sash would be opened by directly pulling on the handle, while the upper sash would also be opened manually, but via a hand crank at the base of the window.

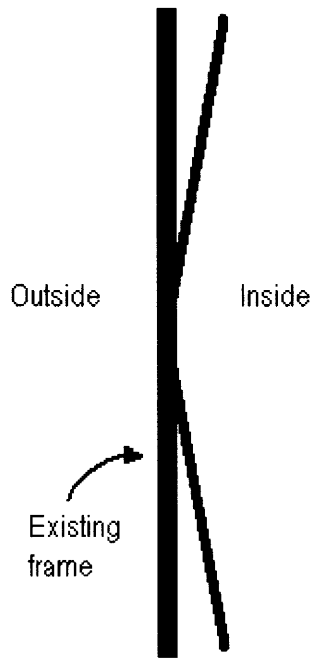


Figure 3
Windows hinged at the middle (A).

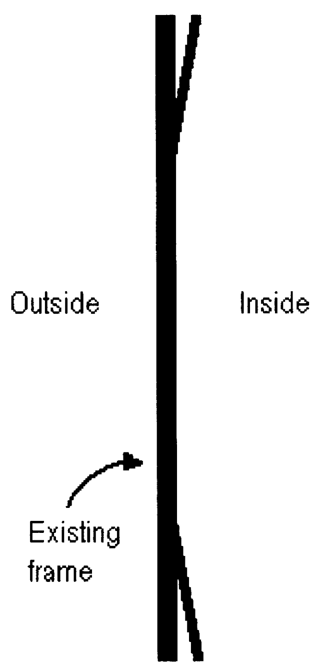


Figure 4
Hinged windows open in opposite directions (B).

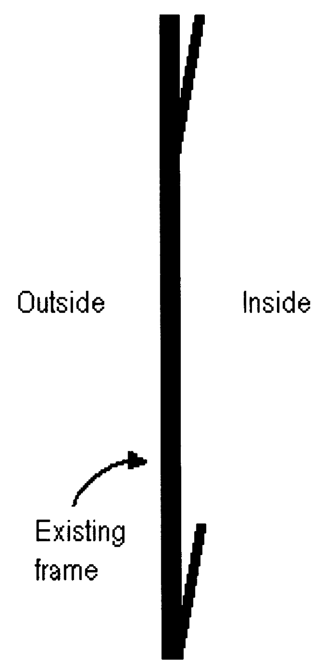


Figure 5
Hinged windows open in the same direction (C).

One concern is whether or not the existing steel frame (meant for single glazed windows) can support the thickness of double glazed windows. Since the existing double hung windows use twice the thickness of steel framework as the rest of the window for the purposes of the counterweight and pulley mechanism, there is sufficient room for double glazed units. In addition, one of the double glazed products considered is the Nippon Spacia Vacuum Glass, and it is cited as being thin enough "to replace a single pane...without changing an existing framing sash in old houses."[7]

A model at 1/8 scale was made from 1/4-inch thick foam core, 1/16-inch thick chipboard, clear plastic sheeting, and Elmer's glue. It was created to visualize the three variations in design and to determine the feasibility and functionality of each. The model was of a first floor window in Building 1, including the set of sliding sashes and the row of glass just below the spandrel panel. The dimensions used were from the northeastern window in room 1-134. The thin muntins were 1.125 inches thick, and the bolded muntins were 1.5 inches thick (see Figs. 6 and 7). Each pane was 16.5 inches wide and 28 inches high.

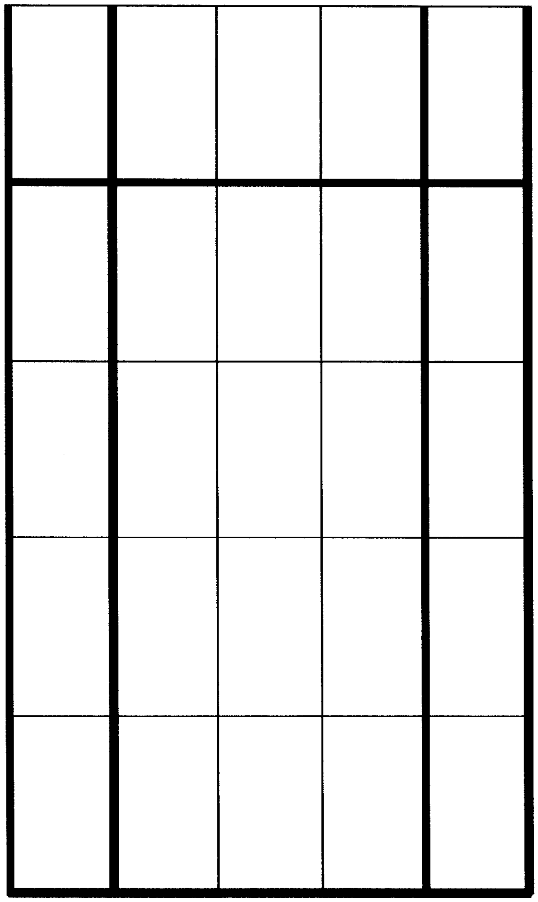


Figure 6
Dimensioning a first floor window in Building 1.

Figure 7
Model of existing window.

From the scale model, it was determined that (A) was not feasible (see Fig. 8). A larger mechanism for opening and closing the window would need to be implemented, and this cost could not be justified since the large structure would have a higher risk of warping. Also, an entire six-pane sash would need to be removed for future replacement or maintenance, compared to the three-pane sashes in (B) and (C).

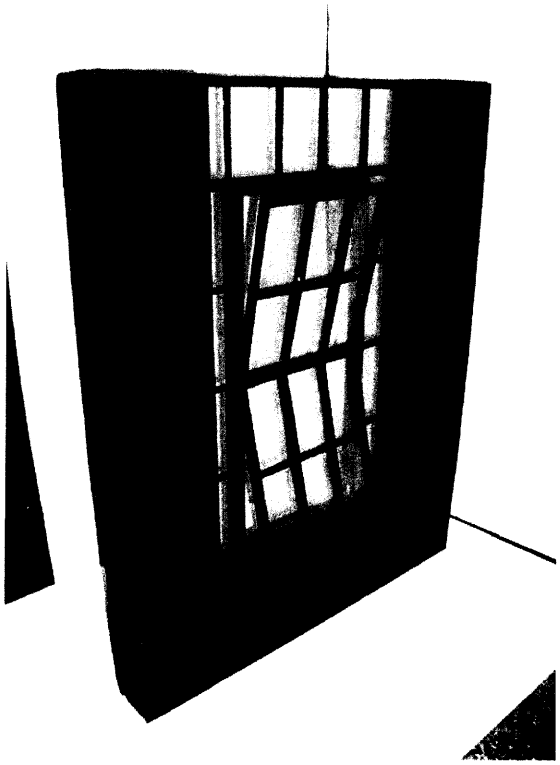


Figure 8
(A) viewed from the interior.

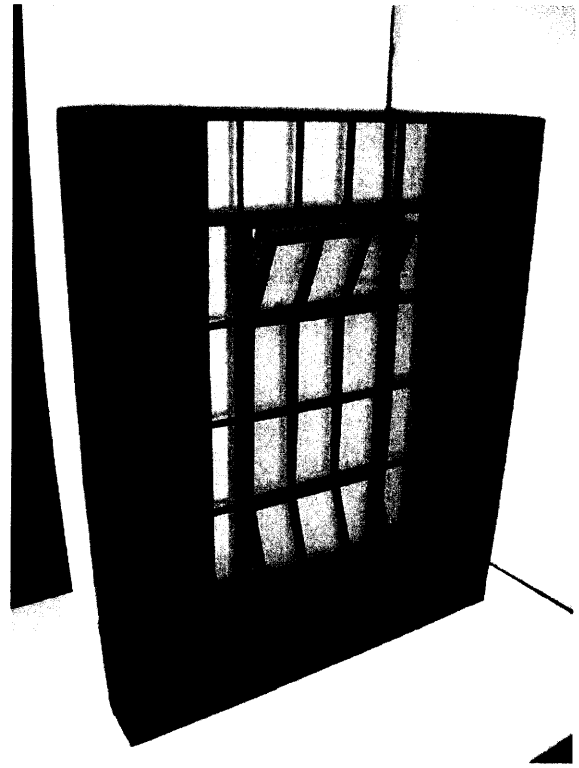


Figure 9
(B) viewed from the interior.

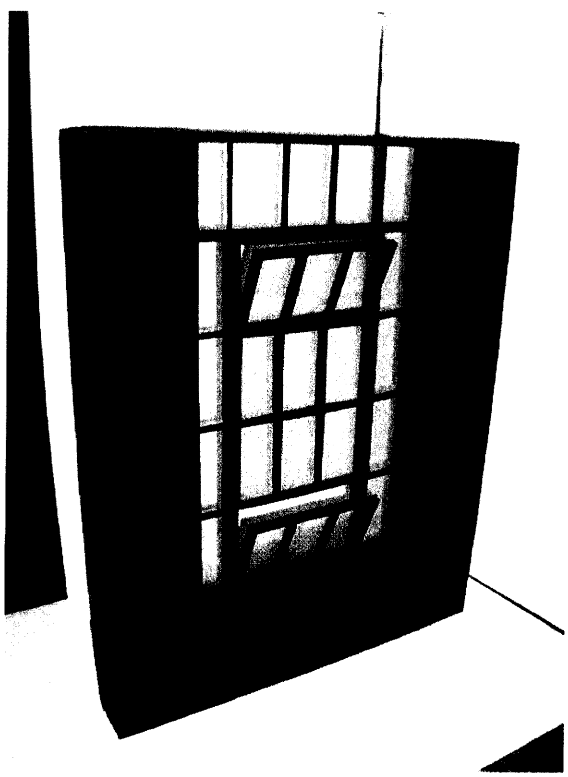


Figure 10
(C) viewed from the interior.

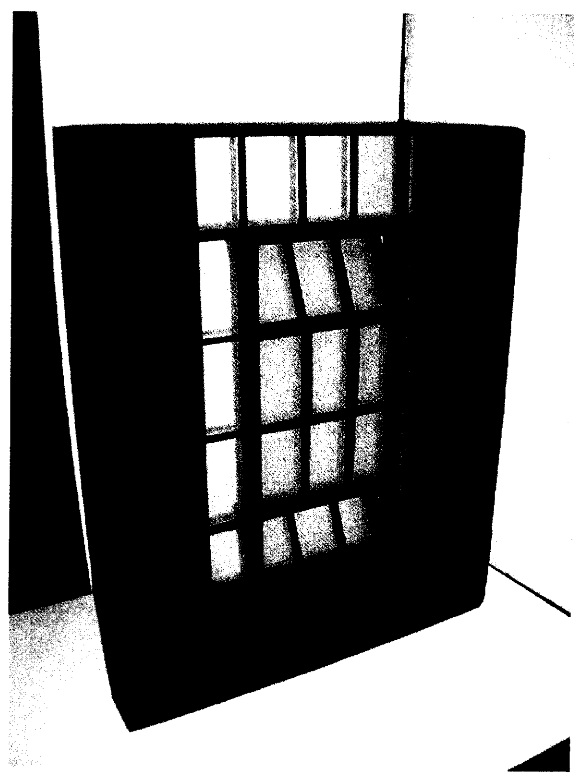


Figure 11
(C) viewed from the exterior.

(B) and (C) are very similar (see Figs. 9 and 10), but (B) has a higher risk of rain penetration. In addition, (C) impedes the least on the interior ledge space which many professors utilize in their offices. Finally, (C) does not significantly affect the façade profile (compare Figs. 7 and 11).

4 Results & Discussion

The new window retrofit clearly demonstrates value in three different ways. Firstly, it contributes to the sustainability of the building by reducing energy loss. Secondly, the retrofit would pay for itself in the energy savings. Finally, occupants of the room experience increased comfort after the window replacement.

4.1 Efficiency Analysis

Heat transfer is determined by the equation

$$Q = UA \cdot \Delta T$$

where U is the overall heat transfer coefficient that accounts for radiation, conduction, and convection, A is the area, and ΔT is the temperature difference across the medium. The total heat transfer involved is the sum of the heat transfer across the steel frame and across the glass window. The U-value of double glazing is much smaller than that of single glazing[8]; hence, there is significantly less energy required to heat a space with double glazed windows. (See Appendix B for complete values and calculations.)

The replacement window would not only reduce the heat loss because of double glazing, but the new framework and compression seals would reduce the heat penalty due to air infiltration. This heat penalty is determined by the equation

$$Q = V \cdot ACH \cdot \Delta T \cdot \rho$$

where V is the volume of the room, ACH is the number of air changes per hour, ΔT is the difference between the inside and outside temperatures, and ρ is the ventilation factor[9], the amount of energy needed to heat one cubic foot one degree Fahrenheit.

Table 1 shows the breakdown in energy loss per window, from the worst-case scenario (existing window) to the best-case scenario (full window replacement). The partial window replacement refers to replacing only the operable sashes with double glazed units. Table 2 shows the breakdown in energy for Buildings 1-11.

Table 1
Energy loss (in BTUs) for a single window.

Scenario	Heat Transfer	Air Infiltration	Total	Savings
Existing	2.35×10^7	7.24×10^7	9.59×10^7	
Partial	1.55×10^7	1.20×10^7	2.75×10^7	6.84×10^7
Full	1.08×10^7	1.20×10^7	2.28×10^7	7.31×10^7

Table 2
Energy loss (in BTUs) for MIT's main campus.

Scenario	Heat Transfer	Air Infiltration	Total	Savings
Existing	3.57×10^{10}	1.1×10^{11}	1.46×10^{11}	
Partial	2.35×10^{10}	1.83×10^{10}	4.18×10^{10}	1.04×10^{11}
Full	1.64×10^{10}	1.83×10^{10}	3.47×10^{10}	1.11×10^{11}

A partial window replacement results in a 71% decrease in heating energy, and a full window replacement results in a 76% decrease. Since most of the energy savings is due to the reduction in air infiltration, there is not a significant difference in energy savings between a partial and a full window replacement.

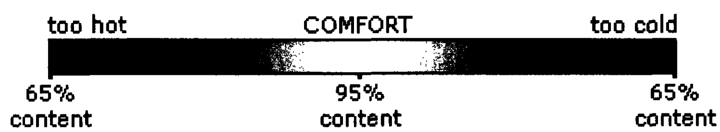
4.2 Cost Savings Analysis

Given a cost of approximately $17 per million BTU of heating energy[10], partial window replacements for all the buildings on the main campus would mean a savings of $1,766,293.20 per heating season. Full window replacements would mean a savings of $1,887,661.30 per heating season.

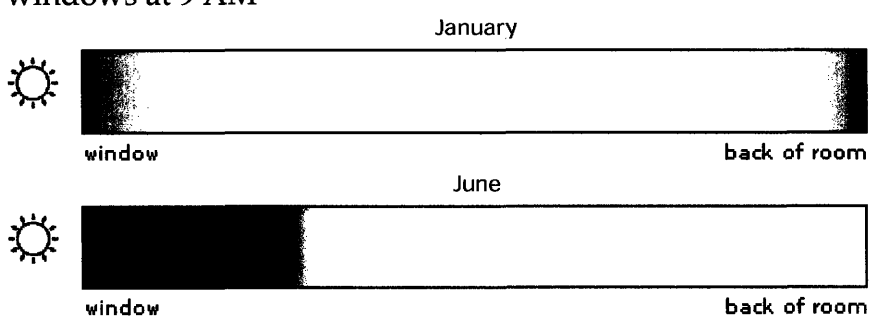
Double glazed units would decrease the solar heat gain into the room, and occupants would close the blinds and turn on the lights less frequently. This results in a decrease in electricity costs. The total realized savings would be more than $1,766,293.20 a year.

4.3 Comfort Analysis using the MIT Design Advisor[11]

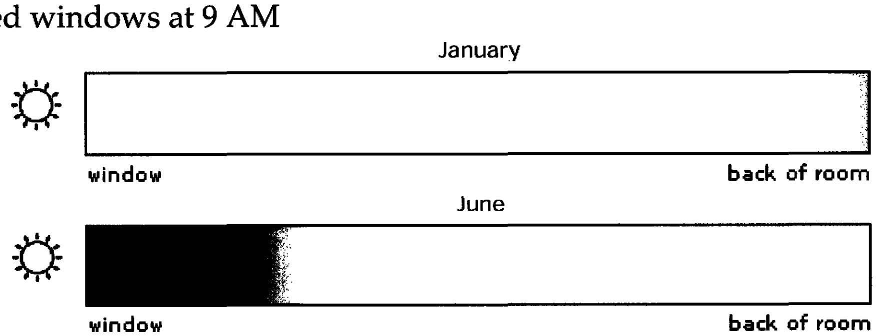
The room's window is oriented south. The variables used in the second scenario setup were based on a partial replacement. (See Appendix C for all the values used in setting up the Design Advisor.) The following figures represent the thermal comfort level within a room as a function of the occupant's distance from the window.



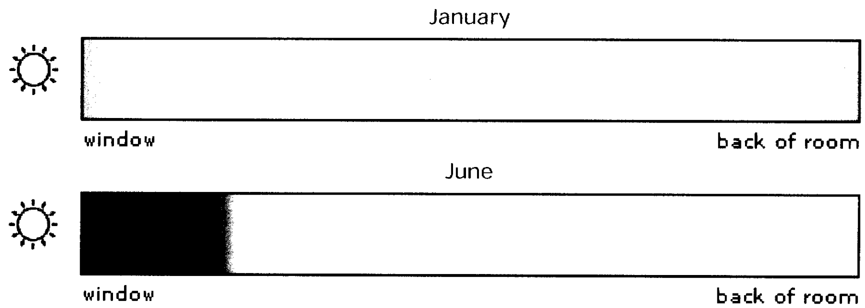
Existing windows at 9 AM



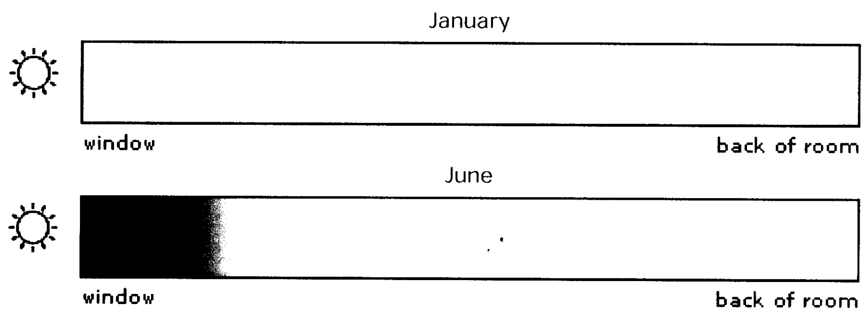
Proposed windows at 9 AM



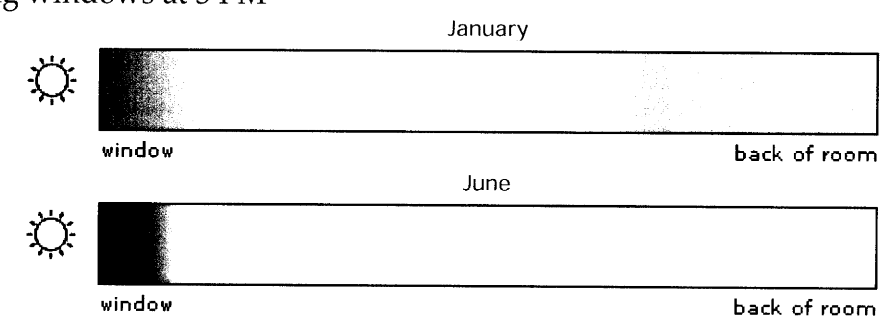
Existing windows at 12 noon



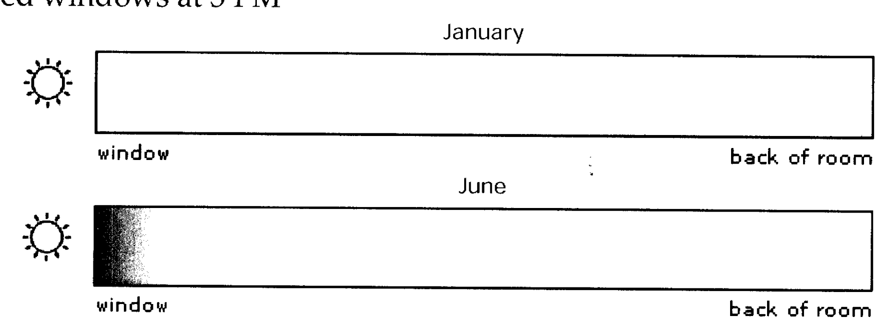
Proposed windows at 12 noon



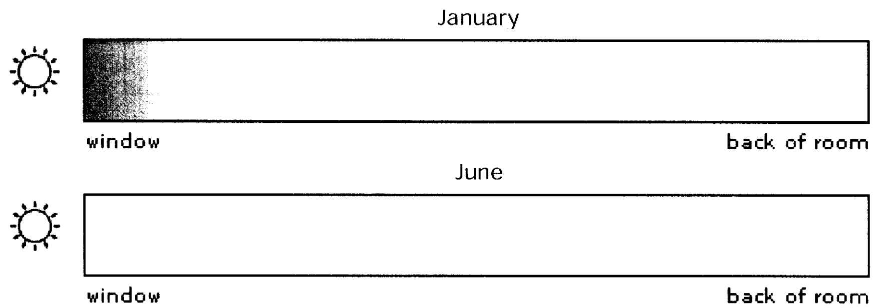
Existing windows at 3 PM



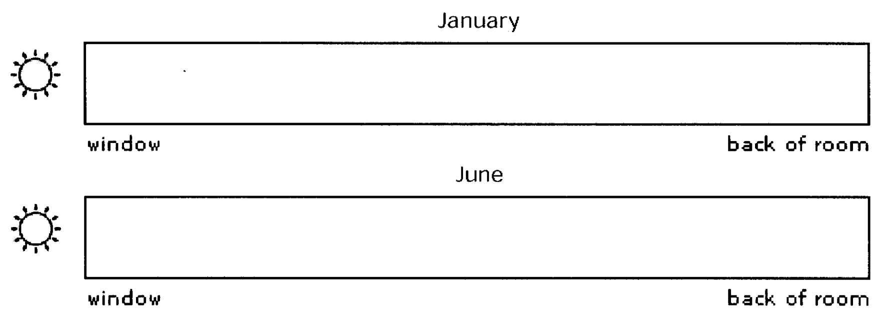
Proposed windows at 3 PM



Existing windows at 6 PM



Proposed windows at 6 PM



All the gradient comparisons show that the proposed windows provide more comfortable conditions throughout the room than the existing windows. In the winter, occupants can be comfortable in all areas of the room at all hours. In the summer, occupants may get warm near the windows before 3 PM, but still more of the room is within a comfort zone than during summertime with the existing windows.

5 Conclusions

I determined that the best variation in design is (C). It is the most functional: the three-pane sashes are easy to open, maintain, and replace; the lower sash which is hinged at the bottom allows the interior ledge space to be used and also minimizes water infiltration; the compression seals reduce air infiltration; and, the vertical ventilation function is maintained. Overall, the aesthetic quality and historical significance of the façade is not changed at all when the windows are closed and changed negligibly when the windows are open.

The analyses show that the window retrofit would be a great improvement in comparison to the current state. The window retrofit would not only increase the comfort level of MIT's students and professors, but it would also allow MIT to demonstrate sustainability initiatives.

Most importantly, this concept can be applied to old buildings outside of the MIT campus as well. Full window restoration or replacement is typically quite expensive, but this window retrofit proves that an affordable solution can still be effective.

6 References

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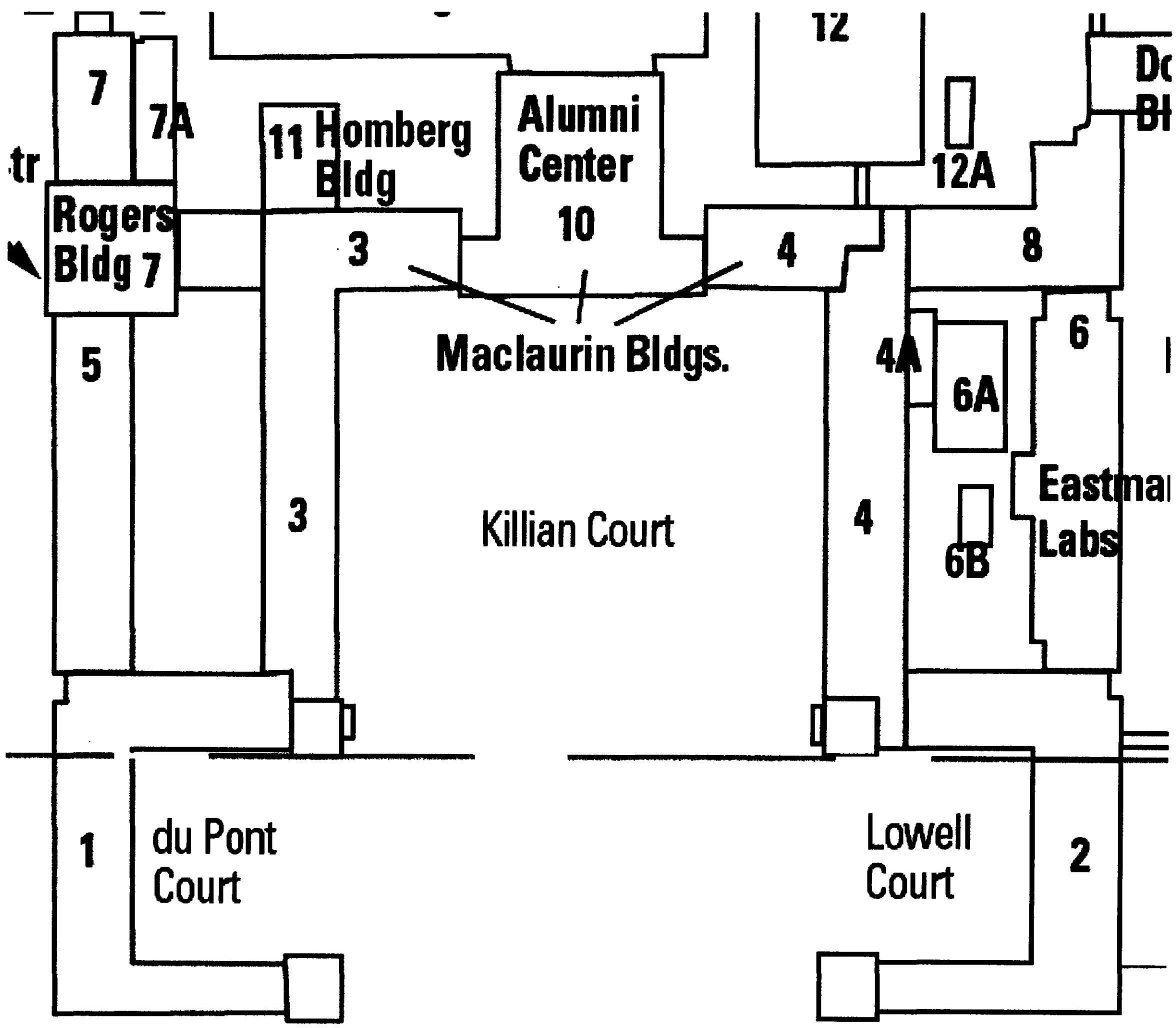
11 MIT Design Advisor. 2005. MIT. April 11, 2007. <http://designadvisor.mit.edu/design/>

Appendix A: MIT Main Group Map

From the MIT website: http://web.mit.edu/campus-map/pdf/campusmap06.pdf



Appendix B: Energy Calculations

These two assumptions are from the MIT class 4.42J Fundamentals of Energy:

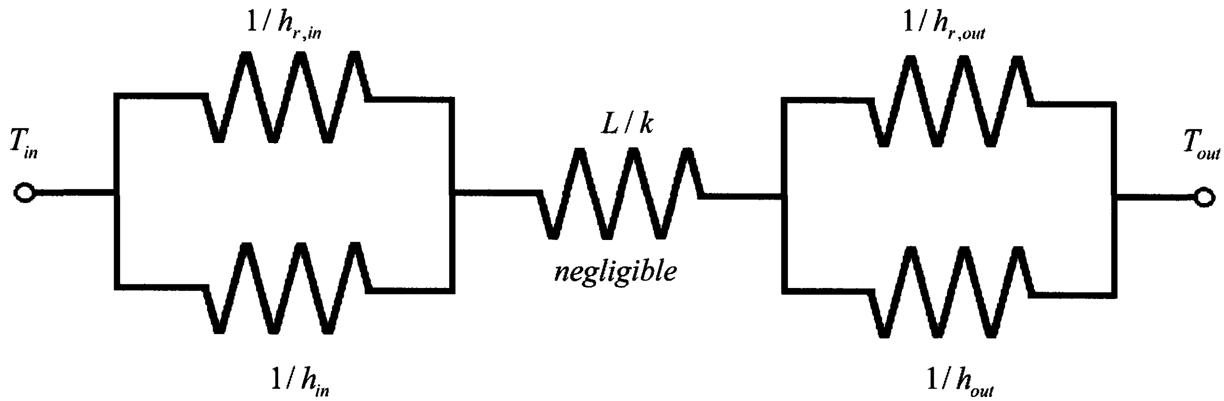
1 Boston averages 5634 degree days for a typical heating year.
2 Inside glass surface radiates to a black body at 0°C (32°F) and outside glass surface radiates to a black body at 20°C (68°F).

B.1 Efficiency Analysis: Heat Transfer

Existing windows:

$$Q_{existing\_total} = Q_{steel} + Q_{existing}$$

The electric analogy for the heat transfer through the steel frame can be drawn as:



$$\begin{aligned}
h_{r,in} &= h_{r,out} = 4\sigma T^3 \\
&= 4(0.1714\times10^{-8} BTU/hr\cdot ft^2\cdot R^4)(50°F + 459.67)^3 \\
&= 0.91 BTU/hr\cdot ft^2\cdot °F \\
R_{steel} &= \frac{1}{h_{r,in}+h_{in}} + \frac{1}{h_{r,out}+h_{out}} = \frac{1}{0.91+10} + \frac{1}{0.91+20} = 0.14 hr\cdot ft^2\cdot °F/BTU \\
U_{steel} &= 1/R = 7.17 BTU/hr\cdot ft^2\cdot °F \\
A_{steel} &= 12.6 ft^2
\end{aligned}$$

$$\begin{aligned}
Q_{steel} &= U_{steel}\cdot A_{steel}\cdot DD \\
&= (7.17 BTU/hr\cdot ft^2\cdot °F)(12.6 ft^2)(5634°F\cdot days)(24 hours/day) \\
&= 1.22\times10^7 BTU
\end{aligned}$$

$$U_{existing} = 1.04 BTU / hr \cdot ft^2 \cdot {}^\circ F \text{ (See Ref. 8)}$$
$$A_{existing} = 80.2 ft^2$$

$$Q_{existing} = U_{existing} \cdot A_{existing} \cdot DD$$
$$= (1.04 BTU / hr \cdot ft^2 \cdot F)(80.2 ft^2)(5634^\circ F \cdot days)(24 hours / day)$$
$$= 1.13 \times 10^7 BTU$$

$Q_{existing\_total} = 2.35 \times 10^7 BTU$ energy loss per window per heating season

Partial replacement windows:

$$Q_{partial\_total} = Q_{steel} + Q_{al} + Q_{remaining} + Q_{partial}$$

$$U_{steel} = 7.17 BTU / hr \cdot ft^2 \cdot {}^\circ F$$
$$A_{steel} = 8.1 ft^2$$

$$Q_{steel} = U_{steel} \cdot A_{steel} \cdot DD$$
$$= (7.17 BTU / hr \cdot ft^2 \cdot {}^\circ F)(8.1 ft^2)(5634^\circ F \cdot days)(24 hours / day)$$
$$= 7.85 \times 10^6 BTU$$

$$U_{al} = 1.0 BTU / hr \cdot ft^2 \cdot {}^\circ F \text{ (See Ref. 5)}$$
$$A_{al} = 4.95 ft^2$$

$$Q_{al} = U_{al} \cdot A_{al} \cdot DD$$
$$= (1.0 BTU / hr \cdot ft^2 \cdot {}^\circ F)(4.95 ft^2)(5634^\circ F \cdot days)(24 hours / day)$$
$$= 0.67 \times 10^6 BTU$$

$$U_{remaining} = 1.04 BTU / hr \cdot ft^2 \cdot {}^\circ F$$
$$A_{remaining} = 41.7 ft^2$$

$$Q_{remaining} = U_{remaining} \cdot A_{remaining} \cdot DD$$
$$= (1.04 BTU / hr \cdot ft^2 \cdot F)(41.7 ft^2)(5634^\circ F \cdot days)(24 hours / day)$$
$$= 5.865 \times 10^6 BTU$$

$$U_{partial} = 0.21 BTU / hr \cdot ft^2 \cdot {}^{\circ}F \text{ (See Table 3)}$$
$$A_{partial} = 38.5 ft^2$$

$$Q_{partial} = U_{partial} \cdot A_{partial} \cdot DD$$
$$= (0.21 BTU / hr \cdot ft^2 \cdot F)(38.5 ft^2)(5634^{\circ}F \cdot days)(24 hours / day)$$
$$= 1.09 \times 10^6 BTU$$

$Q_{partial\_total} = 1.55 \times 10^7 BTU$ energy loss per window per heating season

Table 3
Various glass products used in thermal performance calculations.[3]

Manuf.	*Product*	*Transmittance Visible*	*U-Value*		*SHGC*
			Winter	*Summer*	
Viracon	VE1-2M Solarscreen Low-E Insulating Glass	70%	0.29	0.26	0.38
Viracon	VE1-2M Solarscreen Low-E Insulating Glass with Argon	70%	0.25	0.21	0.37
Viracon	VE1-85 Low-E Insulating Glass with Argon	76%	0.27	0.24	0.54
Viracon	VE15-85 Low-E Insulating Glass with Argon	79%	0.27	0.24	0.62
PPG	Solarban 60 Low-E with Ultraclear Starphire Glass	73%	0.29	0.28	0.41
PPG	Solarban 70XL Low-E with Ultraclear Starphire Glass	63%	0.29	0.27	0.27
Nippon	Spacia Vacuum Glass	68%	0.21	0.21	0.5
Pilkington	Eclipse Pyrolytic Low-E Single Glass	67%	0.53	0.67	0.62
Pilkington	Optiview Anti-Reflective Glass	92%	0.68	0.81	0.77

Full replacement windows:

$$Q_{full\_total} = Q_{steel} + Q_{al} + Q_{full}$$

$$Q_{steel} = 7.85 \times 10^6 BTU$$

$$Q_{al} = 0.67 \times 10^6 BTU$$

$$U_{full} = 0.21 BTU / hr \cdot ft^2 \cdot {}^\circ F$$
$$A_{full} = 80.2 ft^2$$

$$Q_{full} = U_{full} \cdot A_{full} \cdot DD$$
$$= (0.21 BTU / hr \cdot ft^2 \cdot F)(80.2 ft^2)(5634^\circ F \cdot days)(24 hours / day)$$
$$= 2.28 \times 10^6 BTU$$

$Q_{full\_total} = 1.08 \times 10^7 BTU$ energy loss per window per heating season

B.2 Efficiency Analysis: Air Infiltration

Existing windows:

$V = (916{,}828 ft^2)(14.8 ft) = 13{,}569{,}054.4 ft^3$ (See Table 4)
$$ACH = 3$$
$$\rho = 0.02 BTU / ft^3 \cdot {}^\circ F$$

$$Q_{air\_existing} = V \cdot ACH \cdot DD \cdot \rho$$
$$= (13{,}569{,}054.4 ft^3)(3 AC / hr)(5634^\circ F \cdot days)(24 hours / day)(0.02 BTU / ft^3 \cdot {}^\circ F)$$
$= 1.1 \times 10^{11} BTU$ energy loss for main campus per heating season

Replacement windows:

$$V = (916{,}828 ft^2)(14.8 ft) = 13{,}569{,}054.4 ft^3$$
$$ACH = 0.5$$
$$\rho = 0.02 BTU / ft^3 \cdot {}^\circ F$$

$$Q_{air\_replacement} = V \cdot ACH \cdot DD \cdot \rho$$
$$= (13{,}569{,}054.4 ft^3)(0.5 AC / hr)(5634^\circ F \cdot days)(24 hours / day)(0.02 BTU / ft^3 \cdot {}^\circ F)$$
$= 1.83 \times 10^{10} BTU$ energy loss for main campus per heating season

Table 4
Main group area (in square feet)[1].
Note: Assuming the elements are correct, the correct sum is 916,828, not 916,827 as presented in the study.

Main Group Summary		
Use Group	Area (SF)	% of Total
Building Services	16,764	2%
Circulation	184,007	20%
Classrooms	61,820	7%
General Use	22,642	2%
Laboratories	186,779	20%
Mechanical	65,972	7%
Offices	309,456	34%
Special Use	163	0%
Study	30,206	3%
Support	38,722	4%
Unclassified	297	0%
Other	0	0%
Total	**916,828**	

B.3 Cost Savings Analysis

$$Q_{existing\_overall} = Q_{existing\_total} + \frac{Q_{air\_existing}}{1519 windows} = 9.59 \times 10^7\ BTU \text{ loss per window}$$

$$Q_{partial\_overall} = Q_{partial\_total} + \frac{Q_{air\_replacement}}{1519 windows} = 2.75 \times 10^7\ BTU \text{ loss per window}$$

$$Q_{full\_overall} = Q_{full\_total} + \frac{Q_{air\_replacement}}{1519 windows} = 2.28 \times 10^7\ BTU \text{ loss per window}$$

$$Q_{saved1} = Q_{existing\_overall} - Q_{partial\_overall} = 6.84 \times 10^7\ BTU \text{ per window}$$

$$(\$17\ per\ million\ BTU)(68.4\ million\ BTU) = \$1{,}162.80 \text{ saved per partial window}$$

$$Q_{saved2} = Q_{existing\_overall} - Q_{full\_overall} = 7.31 \times 10^7\ BTU \text{ per window}$$

$$(\$17\ per\ million\ BTU)(73.1\ million\ BTU) = \$1{,}242.70 \text{ saved per partial window}$$

Table 5
Savings by building.

Building	Floors	Windows/floor	Windows	Cost savings (partial)	Cost savings (full)
1	3	60	180	209304	223686
2	4	61	244	283723.2	303218.8
3	4	53	212	246513.6	263452.4
4	4	55	220	255816	273394
5	4	33	132	153489.6	164036.4
6	4	30	120	139536	149124
7	4	29	116	134884.8	144153.2
8	4	25	100	116280	124270
9			not part of the main group		
10	5	31	155	180234	192618.5
11	4	10	40	46512	49708
		Total	**1519**	**1766293.2**	**1887661.3**

Appendix C: MIT Design Advisor Setup

Table 6

Variables used for Scenario One (Existing Windows) and Scenario Two (Partial Replacement Windows).

	Existing Windows	Proposed Windows
Simulation Type		
Simulation Type	one_sided	one_sided
Window Description		
Typology	sgu_nb	dgu_nb
Glazing Type	clear	low-e
Window Area	53.60%	53.60%
Wall Description		
Insulation Type	foam	foam
Insulation Thickness	2.0 cm	2.0 cm
Building		
Location	(climate) Boston	(climate) Boston
North-South length	N/A	N/A
East-West length	N/A	N/A
Occupancy		
Type	Classrooms	Classrooms
Occupancy Load	0.25 people per m2	0.25 people per m2
Lighting Requirements	300 lux	300 lux
Equipment Load	1.00 W/m2	1.00 W/m2
Room Ventilation		
Air Change Rate per Occupant	15.0 liters / sec per person	15.0 liters / sec per person
Total Air Change Rate	3.0 roomfuls per hour	3.0 roomfuls per hour
Lighting Control		
Lighting Control	all lights fully on/off	all lights fully on/off
Representative Room		
Orientation	south	south
Room Depth	5.33 m	5.33 m
Room Width	7.24 m	7.24 m
Room Height	4.51 m	4.51 m
Thermal Mass		
Thermal Mass	high	high
Overhang		
Overhang Depth	0 m	0 m